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Clusters of Galaxies - Keys to Cosmology

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ABSTRACT. Various cosmological applications of galaxy clusters are presented. Clusters are used to determine the baryon fraction, dark matter distribution and the matter density Ω_m of the universe. They also contain a wealth of information about structure formation and evolution on different scales: large-scale structure, cluster formation and also galaxy formation via the interaction of cluster galaxies with the intra-cluster medium. In particular, the X-ray satellites CHANDRA and XMM yield exciting new results for galaxy cluster physics and cosmology.

1. Introduction

Clusters of galaxies are used for various kinds of cosmological studies. Clusters can be observed out to large distances and hence they can trace the distribution of matter on large scales. Furthermore, a comparison of the properties of these distant clusters with that of nearby clusters reveals the evolution that clusters undergo between a redshift of 0.5-1 and now. Both large-scale structure and cluster evolution depend sensitively on cosmological parameters. Another interesting point is that clusters are closed systems: no matter can leave the deep potential well. Therefore all the metals that have been processed inside a cluster must still be present, i.e. all the traces of the formation process of the cluster and its galaxies are still observable. Clusters – the largest bound structures in the universe – for many applications can be regarded as being representative of the universe as a whole, because they accumulate matter from a relatively large volume (a few tens of Mpc). Moreover, the crossing time (= the time it takes a galaxy to move from one end of the cluster to the other) is not much smaller than a Hubble time. That means, not all of the traces of the formation process are wiped out, but some information about the early universe is still present.

In the following we will present selected topics which are very promising for cosmology: the distribution of dark and baryonic matter, and a brief overview of various ways to study structure formation and the evolution of different cluster components by investigating their interaction. Throughout this article we use $H_0 = 50$ km/s/Mpc.

2. Distribution of Dark and Baryonic Matter

The deep potential wells of galaxy clusters have accumulated matter from a large volume. Hence the ratio of baryonic to total matter in clusters is representative of the universe as a whole if all the matter is accumulated indiscriminately. Most of the baryons are in the

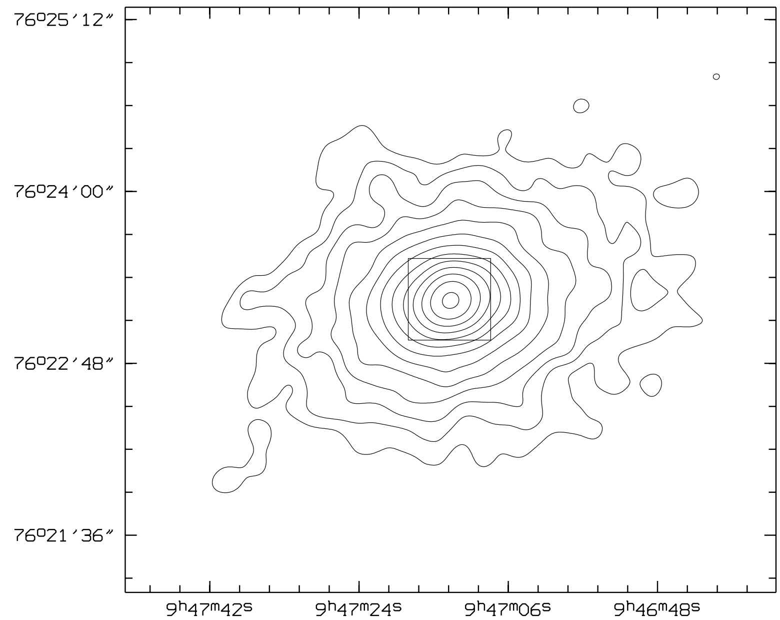

Fig. 1. CHANDRA image of the cluster RBS797. The X-ray emission from the hot gas in the cluster is relatively regular with an ellipticity of 1.3-1.4 in E-W direction. The size of the image is 4.7 arcmin on the side. The central square marks the region shown with higher resolution in Fig. 5.

intra-cluster medium (ICM) – the hot gas that fills all the space between the galaxies (see Fig. 1). Typical values for the gas mass fraction are 10-25%, while the mass fraction in galaxies is only 3-5% of the total cluster mass. Measuring distributions and ratios of baryonic and non-baryonic matter in galaxy clusters is particularly interesting because there are several independent methods to determine the total cluster mass. In this article I will concentrate on the mass determination by X-ray observations. Assuming that the gas traces the potential well (= hydrostatic equilibrium) the total mass can be measured through the X-ray surface brightness distribution and the gas temperature.

This approach is correct only if the magnetic pressure is negligible compared to the thermal pressure. Otherwise the mass is underestimated. To test the influence of the magnetic fields on the mass determination we used magneto-hydrodynamic simulations by Dolag et al. (1999). We found that the magnetic field causes only an underestimation of the total mass in the very centre of relaxed clusters and even there it is only a very small effect of typically not more than 5% (Dolag & Schindler 2000). However, if the clusters are not relaxed, but in the process of merging, the mass can be underestimated considerably. Therefore the mass determination should be either restricted to virialised clusters or be performed very cautiously in clusters which are not in equilibrium.

Several groups determined gas mass fractions from X-ray observations in samples of

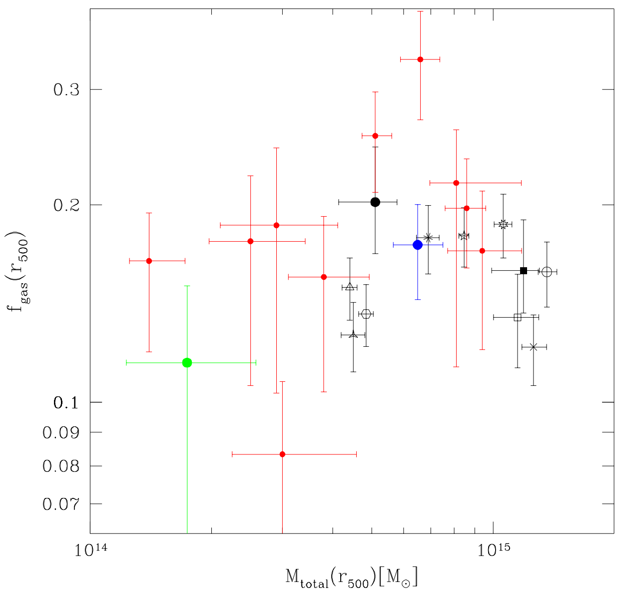

Fig. 2. Gas mass fraction in galaxy clusters versus total mass of the cluster (from Castillo-Morales & Schindler, in prep.).

nearby and distant clusters, e.g. Mohr et al. (1999): $f_{gas} = 0.21$, Ettori & Fabian (1999): $f_{gas} = 0.17$, Arnaud & Evrard (1999): $f_{gas} = 0.16 - 0.20$, Schindler (1999): $f_{gas} = 0.18$ (see also Fig. 2). All these determinations depend on the radius where the mass fraction is determined, because the gas mass fraction increases slightly with radius. Therefore the gas mass fractions have to be calculated for equivalent radii. In the above mentioned analyses the mass was determined within a radius r_{500} from the cluster centre. This radius encompasses a volume that has a density of 500 $\times$ the critical density of the universe ρ_{crit}. Out to this radius the X-ray profiles necessary for the analysis could be measured reliably.

To determine Ω_m, the gas mass fraction f_{gas} must be compared to the baryon density in the universe Ω_B. Burles & Tytler (1998a,b) found $\Omega_B \lesssim 0.08$ from primordial nucleosynthesis. The ratio of the baryon density and the gas mass fraction yields an upper limit for the matter density $\Omega_m < \frac{\Omega_B}{f_{gas}} \approx 0.3 - 0.4$.

The baryon fraction can also be determined in a different way: measurements of the Sunyaev-Zel'dovich effect – inverse-Compton scattering of the Cosmic Microwave Background photons by the hot intra-cluster gas – shifts the CMBR spectrum to slightly higher energies. As this effect is proportional to the gas density, the density profile can be determined directly. Only an additional measurement of the gas temperature is necessary from X-rays. The mean gas mass fraction found by Grego et al. (2001) in a sample of 18 clusters ($f_{gas} = 0.16$) is very similar to the X-ray results. Hence they derive also a

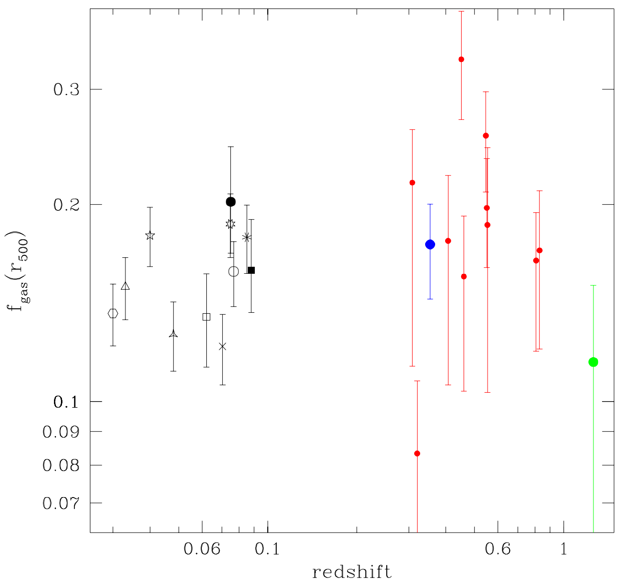

Fig. 3. Gas mass fraction in galaxy clusters versus redshift. The points at z=0.35 and z=1.3 come from CHANDRA observations, all the others use a combination of ROSAT and ASCA data (from Castillo-Morales & Schindler, in prep.).

similar upper limit for the matter density $\Omega_m < 0.4$. In these analyses only the mass in the intra-cluster gas was taken into account. Baryons in the galaxies were neglected. If they were to be included, the baryon fraction would increase slightly and hence ever more stringent constraints on Ω_m could be placed.

For cosmology and cluster formation it is very interesting to know how the baryon fraction in clusters changes with time. In Fig. 3 the gas mass fraction is plotted versus the redshift. It is clear that with the previous ROSAT and ASCA observations it was very hard to see any evolution due to the large observational uncertainties. With XMM and CHANDRA we will be able to measure gas mass fractions out to redshifts of almost unity with good accuracy.

Even with the old observations one can see clearly that the gas fraction varies considerably from cluster to cluster. These different baryon fractions reflect probably the very early distribution of baryonic and non-baryonic matter and they are therefore of high interest for cosmology.

3. Cosmological Structure Formation

Clusters of galaxies can be used to study how structures form on large scales. The formation and evolution of clusters depends very sensitively on cosmological parameters like the mean matter density in the universe Ω_m (Thomas et al. 1998; Jenkins et al. 1998;

Beisbart et al. 2001). Therefore it is of great importance to determine the dynamical state of clusters at different redshifts, i.e. at different evolutionary states.

There are different approaches to determine the dynamical state. X-ray observations yield a projected image of the square of the ICM density and hence they often give a first idea. A much more detailed picture can be obtained through the temperature distribution of the ICM, because shocks and gas compressions due to mergers are visible clearly in temperature maps. The excellent capabilities for spatially resolved spectroscopy of the new X-ray observatories XMM and CHANDRA finally make a detailed temperature analysis possible, see e.g. the temperature maps by Arnaud et al. (2001), Neumann et al. (2001), Markevitch et al. (2000).

Optical observations of the clusters galaxies are also very useful for the determination of the evolutionary state, because both the spatial distribution and the velocity distribution of the cluster galaxies are good indicators.

In the shocks produced during the merging process particles can be accelerated to relativistic energies. These relativistic particles and hence a previous merger event can be detected in two ways. (1) Inverse Compton scattering of photons from the Cosmic Microwave Background Radiation by these relativistic particles can cause a hard X-ray excess in the spectrum, which has been discovered in a few clusters (Fusco-Femiano et al. 1999, 2000, 2001). (2) Due to the presence of magnetic fields, synchrotron radiation is emitted in the form of radio halos (Markevitch & Vikhlinin 2001, Feretti et al. 2001). For a detailed analysis it is necessary to know the distribution of the magnetic field within the cluster. In a recent analysis we found that the magnetic field decreases with radius almost in the same way as the ICM density decreases with radius (Dolag et al. 2001).

Hence, the optimal approach for the determination of the dynamical state is a combination of many wavelengths – X-ray, optical, radio and hard X-ray.

4. Interaction of Galaxies and the Intra-Cluster Gas

The various components in a cluster interact with each other. In particular the interaction between the cluster galaxies and the ICM is very important. Hence this interaction is more and more studied at the different wavelengths. Not only the energy budget and entropy of the ICM are influenced but also the ICM content of heavy elements. The amount of iron in the ICM is e.g. of the same order of magnitude as that in the cluster galaxies (Mushotzky 1999). The heavy elements in the ICM cannot be of primordial origin, but must have been produced in the cluster galaxies and subsequently been transported into the ICM. Several transport processes are possible: ram-pressure stripping, galactic winds, galaxy-galaxy interaction, and jets from active galaxies. So far very controversial results have been obtained in various studies which tried to determine for example the dominant metal enrichment process at a given evolutionary state (see e.g. Metzler & Evrard 1994; Gnedin 1998; Murakami & Babul 1999, Aguirre et al. 2001). If we can find the correct answers, we will learn a lot about galaxy formation and cluster formation.

The new X-ray satellites XMM and CHANDRA revolutionise also this field. It is now possible to measure reliable metallicities out to a redshift of about unity, which was

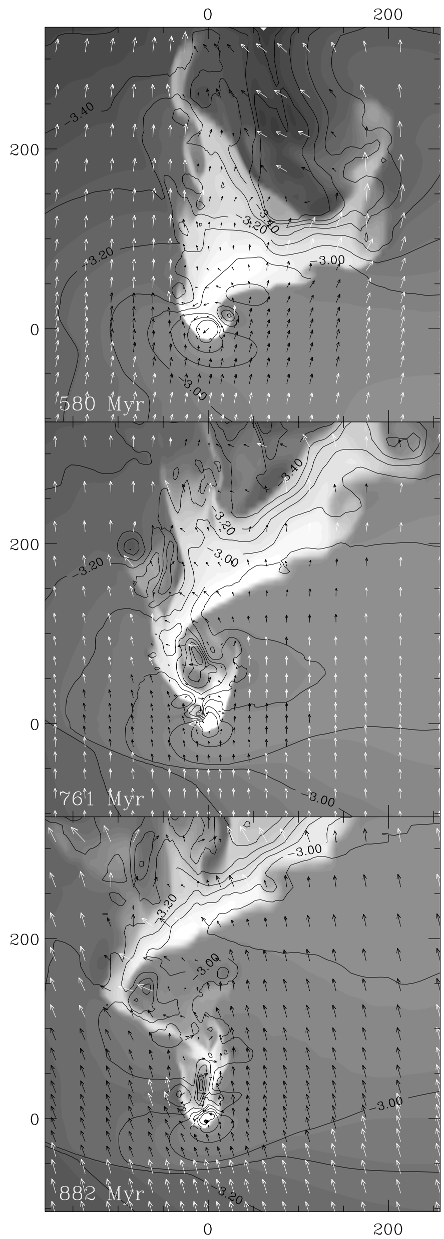

Fig. 4. Gas density (grey scale) and pressure (contours) of a galaxy moving downwards towards the cluster centre. The arrows show the Mach vectors (white when $M > 1$, black otherwise). The gas of the galaxy is stripped due to ram pressure (from Toniazzo & Schindler 2001).

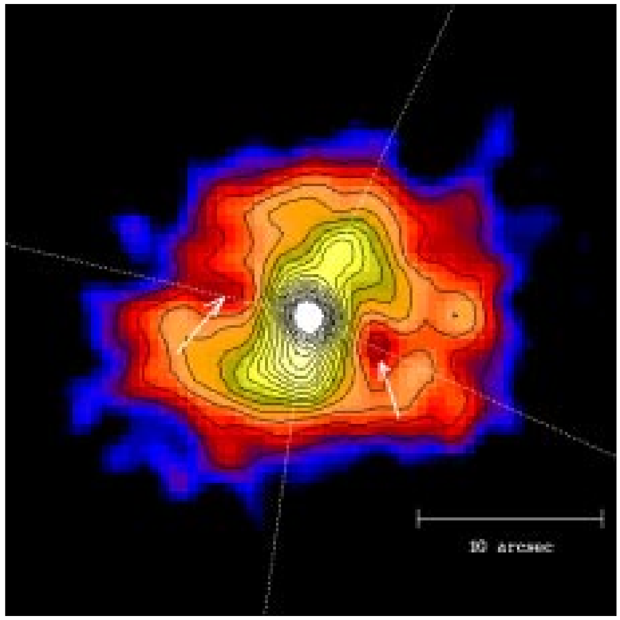

Fig. 5. X-ray image of the central (32 arcsec)^2 of the cluster RBS797. There are clear minima in the X-ray emission at about 5 arcseconds from the cluster centre (see arrows). The minima are opposite to each other with respect to the cluster centre. An excess of emission is found in perpendicular directions. The dotted lines mark the traces shown in Fig. 6.

hardly possible before with e.g. ASCA measurements (Schindler 1999). Furthermore, the metal distribution within the clusters can be measured with much higher accuracy than up to now with e.g. BeppoSAX observations (De Grandi & Molendi 2001). Also different chemical elements can be distinguished now. In order to interpret these excellent new data correctly several numerical simulations have been performed to study the different enrichment processes, for example, ram-pressure stripping of galaxies when they move through the ICM (Abadi et al. 1999, Quilis et al. 2000, Mori & Burkert 2000, Schulz & Struck 2001; Toniazzo & Schindler 2001; see also Fig. 4). Comprehensive simulations on cluster scales will give us new insights into the various metal enrichment processes of the ICM.

5. Selected Highlights from XMM and CHANDRA observations of Galaxy Clusters

Observations of galaxy clusters with the new X-ray satellites XMM and CHANDRA have revealed several surprising results. The high spatial resolution of CHANDRA enables us to look in detail at the cluster centres. In some clusters "depressions" in the X-ray emission have been found, e.g. RBS797 (Schindler et al. 2001, see also Fig. 5 and

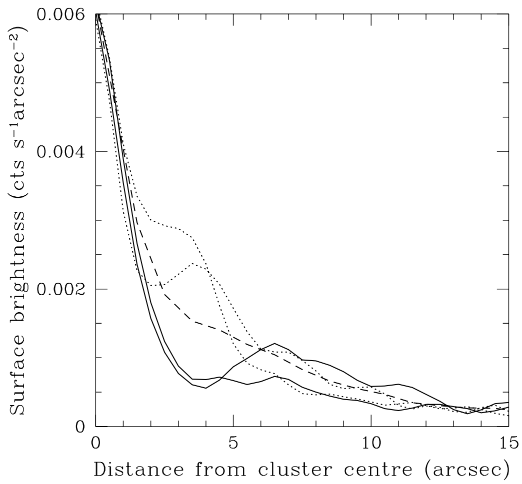

Fig. 6. Dependence of the surface brightness in RBS797 on direction: the X-ray emission from the centre in direction of the minima (solid lines, position angles 77° and 243°, N over E) and in direction of the maxima (dotted lines, position angles 171° and 337°). There is an X-ray deficit of a factor of 3 - 4 in the "holes" compared to the perpendicular directions. The dashed line shows an average profile integrated over all angles.

Fig. 6), Perseus cluster (Fabian et al. 2000), and Hydra-A (McNamara et al. 2000). In these clusters the intra-cluster gas has been pushed from the low X-ray emission regions to the high X-ray emission regions by the pressure of relativistic particles in radio jets, which come from the active galaxy in the cluster centre. These clusters are hence ideal objects to investigate the interaction of jets with the hot intra-cluster medium.

In several CHANDRA observations surprising "edges" have been discovered, e.g. in A3667 (Vikhlinin et al. 2001). These jumps in the X-ray surfaces brightness are not shock fronts, because the temperature increases while the surface brightness drops, i.e. the two sides are in pressure equilibrium. Therefore they were named "cold fronts". They have a width of about 5kpc, which is 2-3 times smaller than the Coulomb mean free path. It is likely that the transport processes here are suppressed by magnetic fields.

The XMM spectra of cooling flow regions in the centres of some clusters revealed that cool gas below a temperature of 1.5keV is absent, e.g. in A1835 (Peterson et al. 2001). This absence of cool gas was very surprising as it provides a serious problem to standard cooling flow models.

6. Summary

Clusters of galaxies are ideal diagnostic tools to determine cosmological parameters in very different ways. In this article only a small selection is presented. The determination of cluster masses and baryon fractions in clusters of galaxies is one of the very active fields at the moment. Also the formation process of clusters is studied in different ways.

Interaction of different cluster components (galaxies, intra-cluster medium) is a topic of increasing interest, because the interaction leaves traces in the metallicities which can be used to infer details of the formation process of clusters and of galaxies. In particular the new X-ray telescopes XMM and CHANDRA yield at the moment extremely exciting results which give new insights in cluster physics and cosmology. These observations will soon answer many of the open questions in cosmology.

Acknowledgements

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References

Abadi, M.G., Moore, B., Bower, R.G., 1999, MNRAS, 308, 947

Aguirre, A., Hernquist, L., Schaye, J., Katz, N., Weinberg, D.H., et al. 2001, astro-ph/0105065

Arnaud M., Evrard A.E., 1999, MNRAS 305, 631

Arnaud, M., Aghanim, N., Gastaud, R., Neumann, D. M., Lumb, D., et al. 2001, A&A 365, L67

Beisbart, C., Valdarnini, R., Buchert, T., 2001, A&A submitted

Burles S., Tytler D., 1998a, ApJ 499, 699

Burles S., Tytler D., 1998b, ApJ 507, 732

De Grandi, S., Molendi, S., 2001, ApJ, 551, 153

Dolag, K., Bartelmann, M., Lesch, H. 1999, A&A, 348, 351

Dolag, K., Schindler, S., 2000, A&A, 364, 491

Dolag, K., Schindler, S., Govoni, F., Feretti, L., 2001, A&A, in press, astro-ph/0108485

Ettori S., Fabian A.C., 1999, MNRAS 305, 834

Fabian, A.C., Sanders, J.S., Ettori, S., Taylor, G.B., Allen, S.W., 2000, MNRAS, 318, L65

Feretti, L., Fusco-Femiano, R., Giovannini, G., Govoni, F., 2001, A&A, 373, 106

Fusco-Femiano, R., Dal Fiume, D., Feretti, L., Giovannini, G., Grandi, P., et al., 1999, ApJ 513, L24

Fusco-Femiano, R., Dal Fiume, D., De Grandi, S., Feretti, L., Giovannini, G., et al., 2000, ApJ 534, L7

Fusco-Femiano, R., Dal Fiume, D., Orlandini, M., Brunetti, G., Feretti, L., et al., 2001, ApJ, 552, L97

Gnedin, N.Y., 1998, MNRAS, 294, 407

Grego L., Carlstrom J.E., Reese E.D., et al., 2001, ApJ 552, 2

Jenkins, A., Frenk, C.S., Pearce, F.R., Thomas, P.A., Colberg, J.M., et al., 1998, ApJ 499, 20

Markevitch, M., Vikhlinin, A., 2001, astro-ph/0105093

Markevitch, M., Vikhlinin, A., Mazzotta, P., VanSpeybroeck, L., 2000, in Proc. "X-ray Astronomy 2000" (Palermo, September 2000), R. Giacconi, L. Stella, S. Serio (eds.), ASP Conference Series, astro-ph/0012215

McNamara, B.R., Wise, R., Nulsen, P.E.J., David, L.P., Sarazin, C.L., et al., 2000, ApJ, 534, L135
Metzler, C.A., Evrard, A.E., 1994, ApJ, 437, 564
Mohr J.J., Mathiesen B., Evrard A.E., 1999, ApJ 517, 627
Mori, M., Burkert, A., 2000, ApJ, 538, 559
Murakami, I., Babul, A., 1999, MNRAS, 309, 161
Mushotzky, R.F., 1999, astro-ph/9912547
Neumann, D. M., Arnaud, M., Gastaud, R., Aghanim, N., Lumb, D., et al., 2001, A&A 365, L74
Peterson, J. R., Paerels, F.B.S., Kaastra, J.S., Arnaud, M., et al., 2001, A&A, 365, L104
Quilis, V., Moore, B., Bower, R., 2000, Science, 288, 1617
Schindler, S., 1999, A&A 349, 435
Schindler, S., Castillo-Morales, A., De Filippis, E., Schwope, A., Wambsganss, J., 2001, A&A Letters, in press, astro-ph/0107504
Schulz, S., Struck, C., 2001, astro-ph/0107570
Thomas, P.A., Colberg, J.M., Couchman, H.M.P., Efstathiou, G., Frenk, C.S., 1998, MNRAS, 296, 1061
Toniazzo, T., Schindler, S., 2001, MNRAS 325, 509
Vikhlinin, A., Markevitch, M., Murray, S. S., 2001, ApJ, 551, 160

DISCUSSION

N. PANAGIA: About the anti-correlation found between X-ray and radio emission, I am wondering which is the cause and which the effect: is it the radio structure that pushes the X-ray emitting gas or, viceversa, is it the hot gas that confines the radio emitting matieral?

S. SCHINDLER: In the current model the pressure of the relativistic particles in the radio jets push away the X-ray emitting gas until the system is in pressure equilibrium.

G. KANBACH: Radio observations show that cosmic ray pressure could influence the intra-cluster medium. Is the cosmic ray pressure generally taken into account in the dynamical balance of the intra-cluster medium?

S. SCHINDLER: So far cosmic ray pressure is usually not taken into account. For standard mass determinations from X-ray observations only the thermal pressure of the intra-cluster medium is taken into account.

W. KUNDT: What topology was assumed for the magnetic field simulations in clusters?

S. SCHINDLER: Different types of initial magnetic seed fields were used: completely homogeneous and also chaotic initial magnetic field structures. This field is amplified by compression during the cluster collapse. It was shown that the final field structure is determined only by the dynamics of the cluster collapse and not by the inital conditions.